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IMPROVED YIELD DETERMINATION AND EVENT IDENTIFICATION RESEARCH

J. T. Cherry
N. Rimer
J. M. Savino
W. O. Wray

Quarterly Technical Report
For Period May 1, 1975 - July 31, 1975

Sponsored by
Advanced Research Projects Agency
ARPA Order No. 2551



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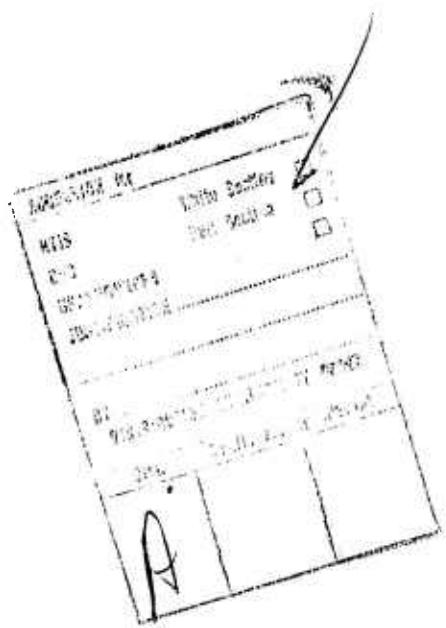
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S³ Project No. 11014

August 8, 1975

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20. the overburden pressure substantially reduces seismic coupling.

The near field coupling and the equivalent elastic source were computed for the recent underground explosion, Mast, at Pahute Mesa. The next step is to generate synthetic seismograms for this event at recently specified receiver locations. The enhanced computational capabilities for treating realistic earth structures will be exercised in this experiment.

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I. SUMMARY

During the past several years, Systems, Science and Software (S³) personnel have been actively engaged in a comprehensive program involving computer modeling of the non-linear processes that characterize underground nuclear explosions, propagation of the resultant stress waves through realistic earth structures and prediction of the ground motion recorded at teleseismic distances from an explosion. The objectives of the subject project are to employ these modeling and predictive capabilities in a systematic examination of the effects of variations in source and emplacement parameters on seismic signals from underground explosions, and to investigate methods for utilizing the general characteristics of seismic waveforms to obtain reliable yield estimates for explosions.

The technical phases necessary to accomplish the objectives of this project are as follows:

1. Conduct a systematic theoretical examination of material, source and emplacement parameters which affect yield-magnitude relationships and compare the theoretical predictions to actual observations.
2. Determine and express uncertainties of yield estimates in terms of uncertainties in gross earth structure, near source material properties, and local source and receiver structure.

Major accomplishments during the first three months of this project were realized in several different areas of research. In particular, a very comprehensive investigation of the sensitivity of seismic magnitudes, which are used to estimate explosion yields, to variations in near source material properties was carried out. By means of this study

several parameters were isolated and systematically varied to determine their relative influence on seismic magnitudes. A discussion and summary of the results of this study form a subsequent part of this report. A technical report describing the results of this parameter study in greater detail is in preparation (Wray, et al. [1]).

Another area of particular importance is the exercise of our ground motion predictive capabilities for specific NTS underground explosions. The near field coupling and the equivalent elastic source (Cherry, et al. [2]) were computed for the recent explosion, Mast, detonated at Pahute Mesa. Information on certain material properties appropriate for the shot medium were provided in a CEP document. Synthetic seismograms will be computed at receiver sites specified by the Project Officer. There are several important questions that we will try to answer as a result of this experiment. For instance, what pre-shot measurements of the near source medium are required in order to be able to predict the seismically determined yield to within some specified range? The results of this experiment have important implications for a Limited Threshold Test Ban Treaty.

Considerable effort was spent on code development during the past three months. A new tension fracture model was developed in the shock code used for modeling the non-linear regime of a nuclear explosion. Additional calculational tools, one that will facilitate modeling of two-dimensional phenomena such as cratering, and another that will provide a more accurate generalized ray theory approach to computing amplitudes of seismic waves traveling through the earth's upper mantle, were added to the S³ library of computer codes.

III. INTRODUCTION

As stated in the previous section the objectives of the subject research project are to utilize existing computational capabilities to examine the effects of various source and emplacement parameters on seismic signals from underground explosions, and to devise and evaluate methods for utilizing the general characteristics of seismic waveforms to obtain reliable estimates of explosion yields. In order to realize these objectives, activity on this program during the first three months of the contract period was concentrated in the following areas:

1. Study of the dependence of teleseismic magnitude on near source material properties.
2. Prediction of teleseismic ground motion for specific NTS explosions.
3. Improvements in computational capabilities.

The plan of the remainder of this report is a technical discussion of each of these three research areas, followed by a section summarizing the most important results obtained to date.

III. TECHNICAL DISCUSSION

3.1 INTRODUCTION

A key requirement for predicting both body and surface wave teleseismic ground motion from a nuclear explosion is the specification of the equivalent elastic source of the explosion. Computational techniques and material models have been developed at S³ which permit a prediction of the equivalent elastic source given the yield of the explosion and the material properties of the near source geologic environment. In the case of a spherically symmetric explosion source a convenient representation of the equivalent elastic source is given in terms of the steady state value of the reduced displacement potential (RDP), $\psi_{(\infty)}$ (Cherry, et al. [2]).

A particularly important relationship between the seismically determined bodywave magnitude, m_b , and ψ_{∞} is

$$m_b \sim \log \left[\frac{\psi_{(\infty)}}{C_0} \right] \quad (3.1)$$

where C_0 is the near source sound speed (Cherry, et al. [2]). This relationship will be used often in the following subsections of this report.

3.2 DEPENDENCE OF TELESEISMIC MAGNITUDE ON NEAR SOURCE MATERIAL PROPERTIES

The basic objective of the study presented in this section is to determine the sensitivity of seismic yield-magnitude relationships to parameters related to the explosive source and the near source material properties. Two distinct source descriptions have been employed and the differences are discussed in subsection 3.2.2. The remaining parameters are numerous and are all related to material description. Since our constitutive models are fairly complex, great care has

been exercised to conduct the sensitivity study in a systematic and meaningful manner. A general discussion of the organization of the sensitivity study and the meaning of the various independent material parameters is presented in the following paragraphs of this subsection.

Figure 3.1 depicts, in flow chart form, the computational organization followed in the one-dimensional parameter study. The study begins with a material composed of a mixture of tuff and water which may contain air-filled voids. The properties of the water and compacted tuff constituents are held constant for all calculations. The water is described by an equation of state formulation developed by Bjork and Gittings^[3] and the formulation given by Riney, et al.^[4] is used for tuff with a grain density of 2.4 gm/cm. The mass fraction of water in the mixture, f_w , is a natural parameter to select for initial variation and this choice is indicated in Fig. 3.1 which contains a "flow chart" of the sensitivity study. The water content study was conducted by varying f_w in a material with no air-filled voids; the procedure and results are discussed in subsection 3.2.1.

The remaining material parameters are varied one at a time while holding the water mass fraction constant at 0.17. Four of these material parameters are directly related to the porosity model which is discussed by Cherry, et al.:^[5] (1) the air-filled volume fraction, ϕ_0 ; (2) the elastic limit of the pressure, P_e ; (3) the crush or compaction pressure, P_c ; (4) the bulk modulus, k . It should be recognized that k may not be varied with complete freedom, after the constituent properties and the mass fraction of water are fixed, without violating consistency requirements. For the second independent elastic property of the porous mixture we select the shear or rigidity modulus, μ . The compressional wave velocity, c , equals $\frac{\sqrt{k + 4/3 \mu}}{\rho}$

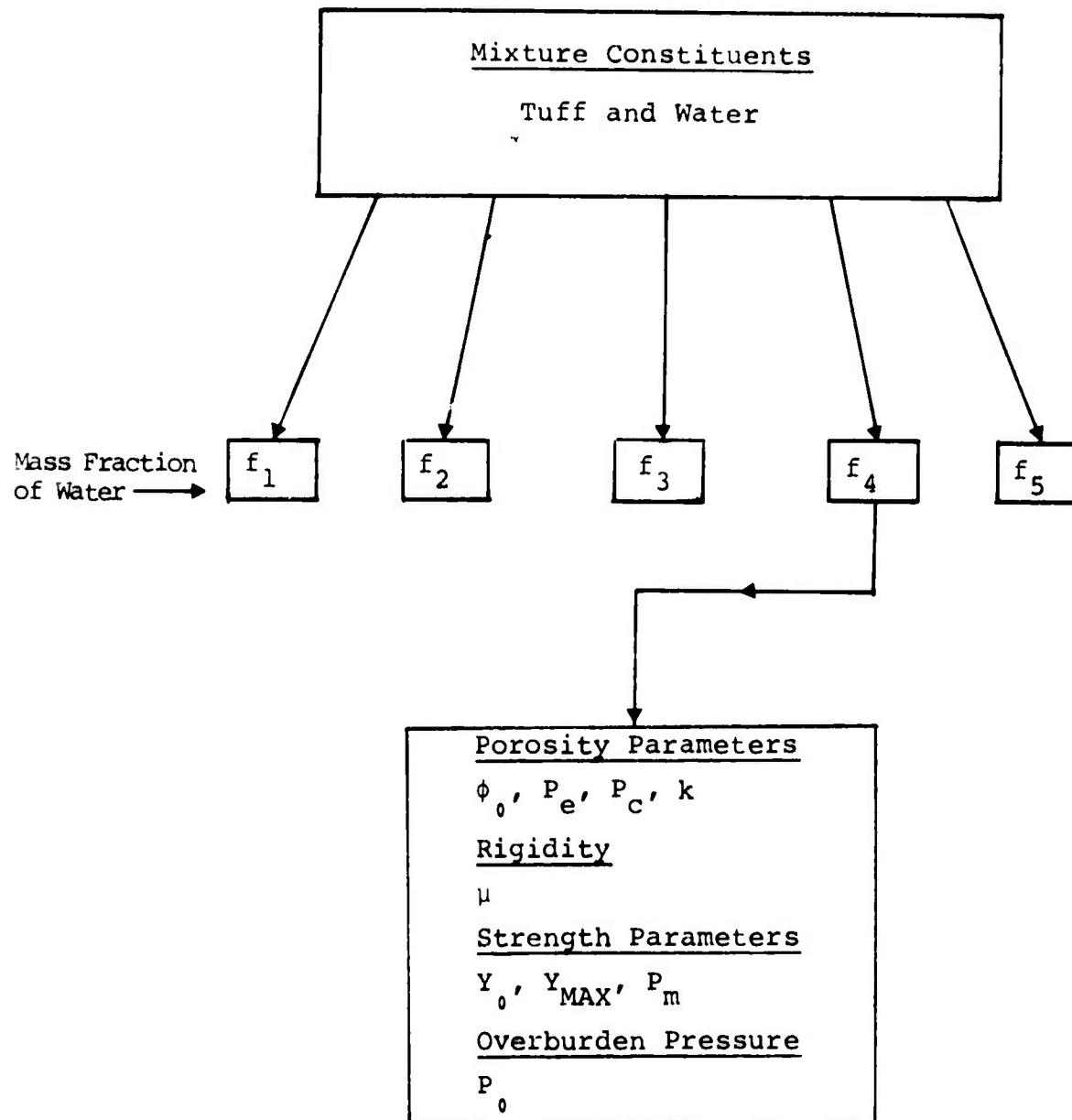


Figure 3.1. Flow chart for one-dimensional sensitivity study.

Three additional material parameters are contained in the pressure and energy dependent model for the yield strength. The yield strength, γ , is given by

$$\begin{aligned}\gamma &= \left[\gamma_0 + \gamma_m \frac{P}{P_m} \left(2 - \frac{P}{P_m} \right) \right] \left(1 - \frac{e}{e_m} \right), \quad P < P_m \\ &\qquad\qquad\qquad e < e_m \\ &= \left(\gamma_0 + \gamma_m \right) \left(1 - \frac{e}{e_m} \right), \quad P \geq P_m \\ &= 0, \quad e \geq e_m\end{aligned}\tag{3.2}$$

where γ_0 is the zero pressure value of the yield strength, $\gamma_{MAX} = \gamma_0 + \gamma_m$ is the maximum yield strength, P is the pressure, P_m is the pressure at maximum yield strength, e is the energy density and e_m is the energy density at incipient melt. The melt energy is associated with the tuff and is therefore not varied leaving the independent parameters γ_0 , γ_{MAX} , and P_m .

One last parameter, the overburden pressure, P_o , is included in the one-dimensional sensitivity study. Even though the overburden pressure is a depth of burial parameter it is included as part of the parameter study.

3.2.1 Water Content Parameter Study

The effects of water content on seismic coupling were studied using SKIPPER,^[6] a one-dimensional Lagrangian non-linear wave propagation code. The reduced displacement potential (RDP) was calculated for five fully saturated tuffs having different mass fractions of water (f_w). Fully saturated tuffs were chosen for this study in order to eliminate the effects of air-filled voids.

The tuffs were modeled using the Tabular Array of Mixtures Equation Of State (TAMEOS). For a given mass fraction of water, the TAMEOS scheme mixes dry rock, modeled by a Mie-Gruneisen equation of state, with water, assuming that the

components of the mixture are in pressure equilibrium. Thus, the pressure, specific volume, and specific internal energy of the mixture (P_m , V_m , and e_m respectively) are given by the following equations:

$$\begin{aligned} P_m &= P_r = P_w \\ V_m &= (1 - f_w)V_r + f_w V_w \\ e_m &= (1 - f_w)e_r + f_w e_w \end{aligned} \quad (3.3)$$

where the subscripts r and w refer to the rock and water components.

Five calculations were made for tuffs with material properties as given in Table 3.1 and for a nominal device yield of 20 tons. Adding water decreases both the density, ρ_0 , and bulk modulus K_M of the mixture. Since the shear modulus was held constant at 40 kbars for all calculations, the variation in longitudinal sound speed C_0 reflects only the change in bulk modulus. Figure 3.2 represents graphically the results shown in Table 3.1. RDP decreases as more water is added into the mixture. RDP/C_0 , a measure of the seismic amplitude, is also plotted. This also decreases as water content is increased.

The decrease in seismic coupling, as the amount of water in the water-rock mixture is increased, is to be expected. Since water is more compressible than rock, the amount of energy dissipated in the form of heat via shock loading increases with increasing water content, resulting in less energy available for conversion into seismic radiation.

The column headed Δm in Table 3.1 gives an indication of the change in teleseismic magnitude as a function of water content. The calculation for $f_w = 0.19$ was chosen as the reference point. The calculation of Δm values is based

TABLE 3.1
SUMMARY OF WATER CONTENT STUDY

f_w	ρ_0 (gm/cm ³)	K_M (kbars)	C_0 (km/sec)	RDP (meters ³)	RDP/C_0 (cm ² /sec)	Δm
0	2.400	294.4	3.81	13.88	36.5	0.088
.05	2.243	121.8	2.80	10.01	35.8	0.081
.136	2.015	66.5	2.44	7.85	32.2	0.034
.17	1.938	57.8	2.40	7.34	30.6	0.012
.19	1.895	53.8	2.38	7.09	29.8	0.0

on Eq. (3.1) and is given by

$$\Delta m = m_1 - m_2 = \log \left[\frac{\psi_1(\infty)/C_0}{\psi_2(\infty)/C_0} \right] \quad (3.4)$$

where $\psi_1(\infty)$ and $\psi_2(\infty)$ correspond to two sets of material properties in Table 3.1 and likewise for the sound speeds C_1 and C_2 . The significant point about the Δm values in Table 3.1 is that for a variation of the mass fraction of water of 19 percent the change in magnitude is only 0.09 units. As we shall see in the next subsection of this report, there are several other parameters that exert a stronger influence on magnitude.

3.2.2 The Effect of Source Description, Unconfined Yield Strength, Seismic Velocity and Shear Modulus on Seismic Magnitudes

The effect of source description and material properties on the RDP were determined by performing calculations with the SKIPPER code. A recent S³ report^[2] identifies and describes a number of material parameters that strongly influence teleseismically recorded ground motion from an underground explosion and presents the results of a sensitivity study performed on those parameters. The results of that study are presented here in Table 3.2 for convenience. All calculations in the table were performed with a near source sound speed, C_0 , of 2.4 km/sec, a shear modulus, μ , of 40 kbar, an unconfined yield strength, Y_0 , of zero, a water mass fraction, f_w , of 0.17, and an explosive yield of 20 tons.

The source description employed in the previous study^[2] made use of a subroutine which computed the radial stress on the cavity boundary via an isentropic relation for a gamma law gas. In order to avoid excessively high pressures in the earth material the maximum pressure obtained for the cavity

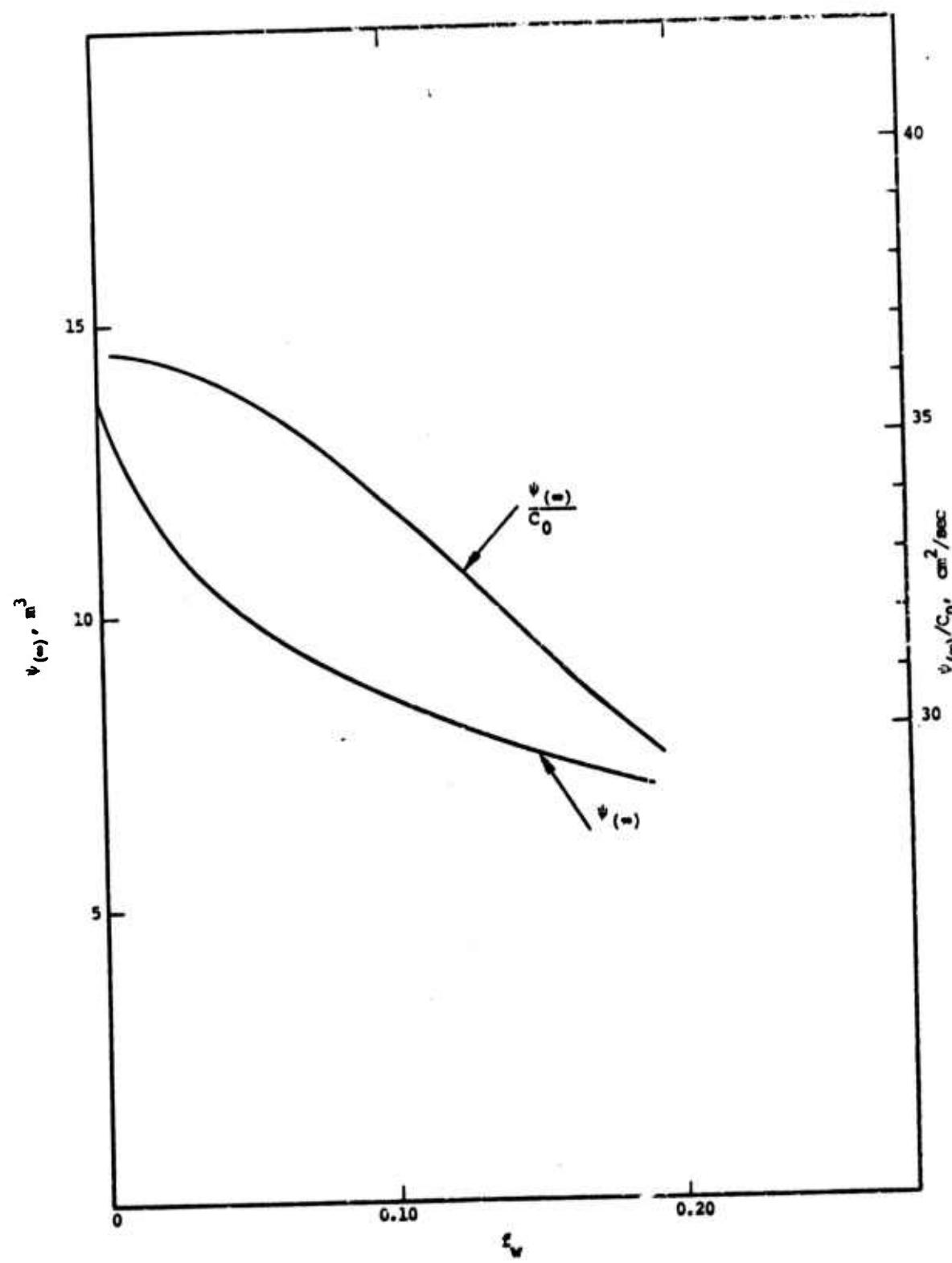


Figure 3.2. Dependence of RDP and seismic coupling on variations in the amount of water in the rock-water matrix.

TABLE 3.2
SUMMARY OF PARAMETER STUDY USING ORIGINAL SOURCE DESCRIPTION

ϕ_0	P_e (kbar)	P_c (kbar)	P_m (kbar)	Y_{MAX} (kbar)	P_0 (kbar)	ρ_0 (g/cc)	$\psi(\infty)$ (m ³)	Δm (m ³)	Calculation No.
0	--	--	0.6	0.5	0.116	1.94	7.4	0.739	(1)
0.02	0.075	0.5	0.6	0.5	0.116	1.90	3.6	0.426	(6)
0.05	0.075	0.5	0.6	0.5	0.116	1.84	2.1	0.192	(4)
0.02	0.075	0.5	0.6	0.5	0.075	1.90	4.2	0.493	(9)
0.02	0.075	0.5	0.6	0.5	0.348	1.90	2.41	0.252	(11)
0.02	0.075	0.5	0.6	0.5	0.619	1.90	2.08	0.188	(12)
0.02	0.075	1.25	0.6	0.5	0.075	1.90	4.6	0.532	(10)
0.05	0.15	1.25	0.6	0.5	0.116	1.84	3.3	0.388	(3)
0.05	0.075	0.5	0.6	1.0	0.116	1.84	1.35	0	(5)
0.02	0.075	0.5	1.25	0.5	0.075	1.90	7.7	0.756	(7)

was not applied to the boundary instantaneously. Instead the cavity pressure was required to approach the maximum value in small increments taken over approximately 50 cycles.

For the new sensitivity calculations reported herein, a more direct procedure is employed for the source description. The total initial energy of the cavity is determined directly from the device yield. The initial cavity radius (radius of vaporization) varies as the one-third power of the energy yield and is determined by the methods discussed by Butkovich.^[7] The initial energy density of the cavity is of course determined by the total energy divided by the total mass. The cavity material is described by a Tillotson equation of state which limits to an ideal gas law at high energies. A single spherical zone is used to model the cavity region; the cavity zone is fully coupled to the adjacent unvaporized earth material zones via the conservation laws of hydrodynamics. No ramping procedure is employed. Several calculations have shown that this procedure conserves energy from the source to within a few percent and that more energy is coupled into the ground than with the old source description; calculated seismic magnitudes are therefore higher. In order to determine the impact of the new source description on the present sensitivity calculation, baseline calculation No. 5 in Table 3.2 was repeated. The new source description gave an RDP, $\psi(\infty)$, of 1.92 cm^3 which is 42 percent higher than the old value of 1.35 m^3 .

Results of the new sensitivity calculations are presented in Table 3.3. The parameters ϕ_0 , P_e , P_c , P_m , P_0 and f_w (or ρ_0) were held constant at the values presented for calculation No. 5 in Table 3.2. The near source seismic velocity, c , the shear modulus, μ , and the unconfined yield strength, Y_0 , were varied systematically. Calculation No. 13 in Table 3.3 is identical to calculation No. 5 in Table 3.2 except that the new source description was used in Table 3.3. The change in

TABLE 3.3
SUMMARY OF MATERIAL PARAMETER SENSITIVITY STUDY
USING NEW SOURCE DESCRIPTION

c (km/sec)	μ (kbar)	γ_0 (kbar)	$\psi(\infty)$ (m^3)	Δm	Calculation No.
2.40	40	0	1.92	0.0606	13
2.32	40	0	1.87	0.0638	14
2.25	40	0	1.84	0.0701	15
2.40	42	0	1.82	0.0374	16
2.40	45	0	1.67	0.0	17
2.40	40	0.1	1.88	0.0514	18
2.40	40	0.2	1.86	0.0467	19

teleseismic magnitude, Δm , is given by Eq. (3.4). Note that calculation No. 17 has been selected as the reference in Table 3.3.

Referring to Table 3.3 (calculations 13, 18, and 19) we see that increasing the unconfined yield strength, Y_0 , decreases the seismic magnitude. This result is consistent with earlier calculations which showed that increasing Y_{MAX} and decreasing P_m both cause the seismic magnitude to be lowered. In general, if any parameter is varied such that the strength of the material is enhanced, the seismic magnitude will be reduced. Calculations 13, 16, and 17 indicate that increasing the shear modulus reduces ground motion coupling. Finally, calculations 13, 14, and 15 show that increasing the sound speed also decreases seismic magnitude.

3.3 PREDICTION OF TELESEISMIC GROUND MOTION FROM THE PAHUTE MESA EXPLOSION, MAST

Reported here is a calculation, using the SKIPPER code, of the near source seismic coupling of Mast, a nuclear event detonated recently in the rhyolite lava of Pahute Mesa. We were provided with a CEP document that summarized data on the material properties for Mast.

Additional material properties data were deemed necessary, however, in order to define an equation of state. In particular, no information was available on shear modulus, bulk modulus, or failure surface. Since hydrostatic load-unload data were also not available, we chose to use the TAMEOS fast table lookup mixture equation of state scheme. Recognizing that the given sound speed was quite high, and therefore both the bulk modulus and shear modulus must be large, a high bulk modulus was chosen for the rock component. The TAMEOS scheme assumes pressure equilibrium between the rock and water components and the mixture. The bulk modulus of the mixture, K_M , is related to the bulk moduli of water and rock (K_W and K_R)

respectively) as follows:

$$\frac{1}{K_M} = \frac{X_W}{K_W} + \frac{X_R}{K_R} \quad (3.5)$$

where X_W and X_R are the volume fractions of water and rock respectively. For the given amount of water for Mast, at zero pressure, the bulk modulus of the mixture can be at most 204 kbars, even for very large K_R , according to the mixture assumptions. At the overburden pressure of 200 bars computed from DOB and effective overburden density, the TAMEOS scheme gave 207.2 kbars for K_M .

Data were available for Halfbeak, a shot detonated previously in a similar rhyolite medium, which showed a Poisson's ratio of approximately 0.18. Since the Halfbeak and Mast working points are very similar, this Poisson's ratio was chosen for Mast. The resulting shear modulus of 168.8 kbars was consistent with both K_M and the given sound speed.

In the absence of any data, and since rhyolite is a relatively hard, competent rock, a failure surface identical to one used successfully for Piledriver, a shot in granite, was chosen for Mast. This surface was parabolic in shape and is given by

$$\begin{aligned} Y &= Y_m \frac{P}{P_m} \left(2 - \frac{P}{P_m} \right) \left(1 - \frac{e}{e_m} \right) & P < P_m, e < e_m \\ Y &= Y_m \left(1 - \frac{e}{e_m} \right) & P \geq P_m, e < e_m \\ Y &= 0 & e > e_m \end{aligned} \quad (3.6)$$

where e_m , the melt energy, is 2×10^{10} ergs/gm, $P_m = 9$ kbar, and $Y_m = 8$ kbars. This surface corresponded to laboratory data for granite. In order to include macroscopic effects of in situ rocks, (fracturing, pore pressure, etc.), whenever a

rock element exceeded a pressure P_L of 0.5 kbars, the yield strength Y was based on P_L rather than P . In spherical geometry, the von Mises yield surface degenerates into a single expression $|S_{10}| \leq \frac{2}{3} Y$, where S_{10} is the deviatoric stress in the radial direction. For any rock element in which pressure had exceeded P_L , the deviatoric stress was allowed to relax toward a lower yield strength Y_R of 0.3 kbar according to the prescription

$$S_{10} = S_{10} - \frac{\Delta t}{\delta} \left(S_{10} - \frac{2}{3} Y_R \right) \quad (3.7)$$

where Δt is the time step of the calculation and δ is a constant, chosen to be 20×10^{-6} sec. This relaxation is conceptually similar to a Maxwell solid and introduces viscoelasticity into the material model for high stresses.

Using the above material modeling, a SKIPPER calculation was made for a nominal device yield of 20 tons. Figure 3.3 shows peak stress versus range and Fig. 3.4 peak velocity versus range for this calculation. In Fig. 3.4, a discontinuity in peak velocity is noted at a range of approximately 18 meters, corresponding to the boundary between a high stress viscoelastic region, where relaxation of the deviatoric stresses is allowed, and a region where relaxation is not permitted.

In order to determine the seismic coupling, the calculation was continued until the response of the rock-water mixture became elastic. Displacement, velocity, radial stress, and reduced displacement potential (RDP) were monitored at a station in the rhyolite located 132 meters from the working point. Figures 3.5 - 3.8 show plots of these quantities versus time. The steady state value of RDP, defined as ηx_0^2 where η is the static displacement at position x_0 , was computed at many stations, all giving $6.9 \times 10^6 \text{ cm}^3$. Thus, the material response is in fact elastic. The RDP $\psi(\infty)$, is a measure of seismic

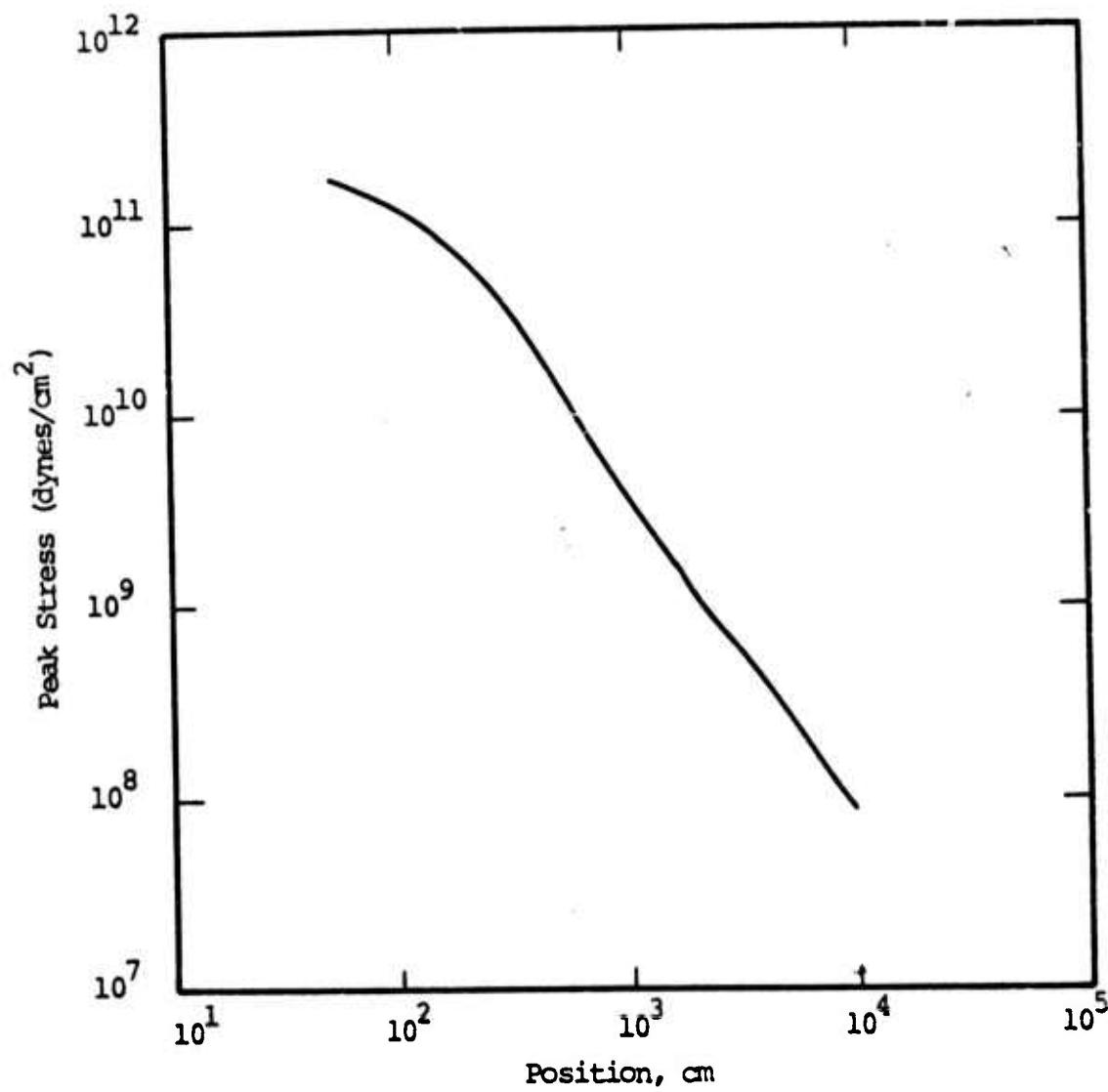


Figure 3.3. Peak stress versus range for Mast.

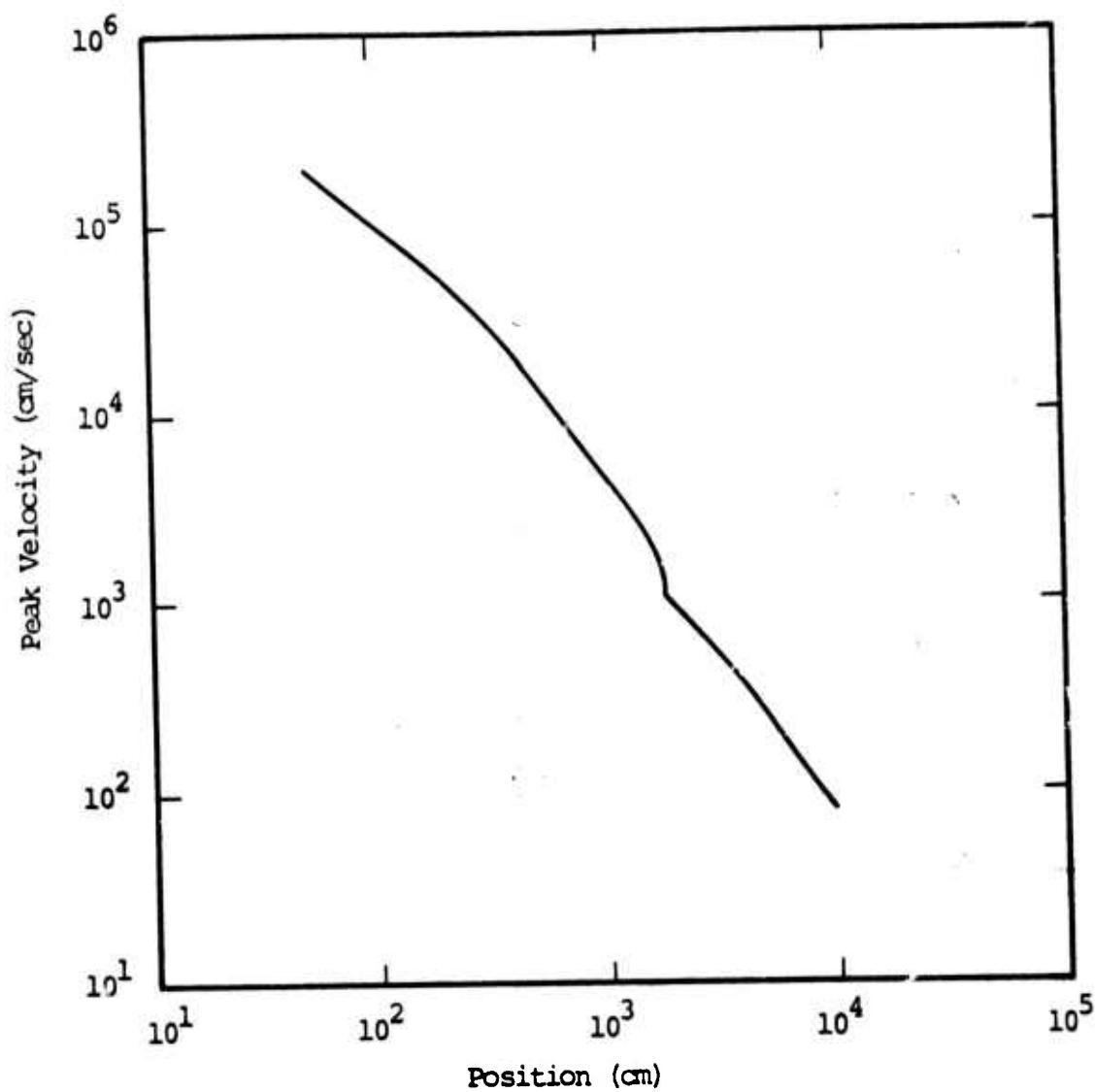


Figure 3.4. Peak velocity versus range for Mast.

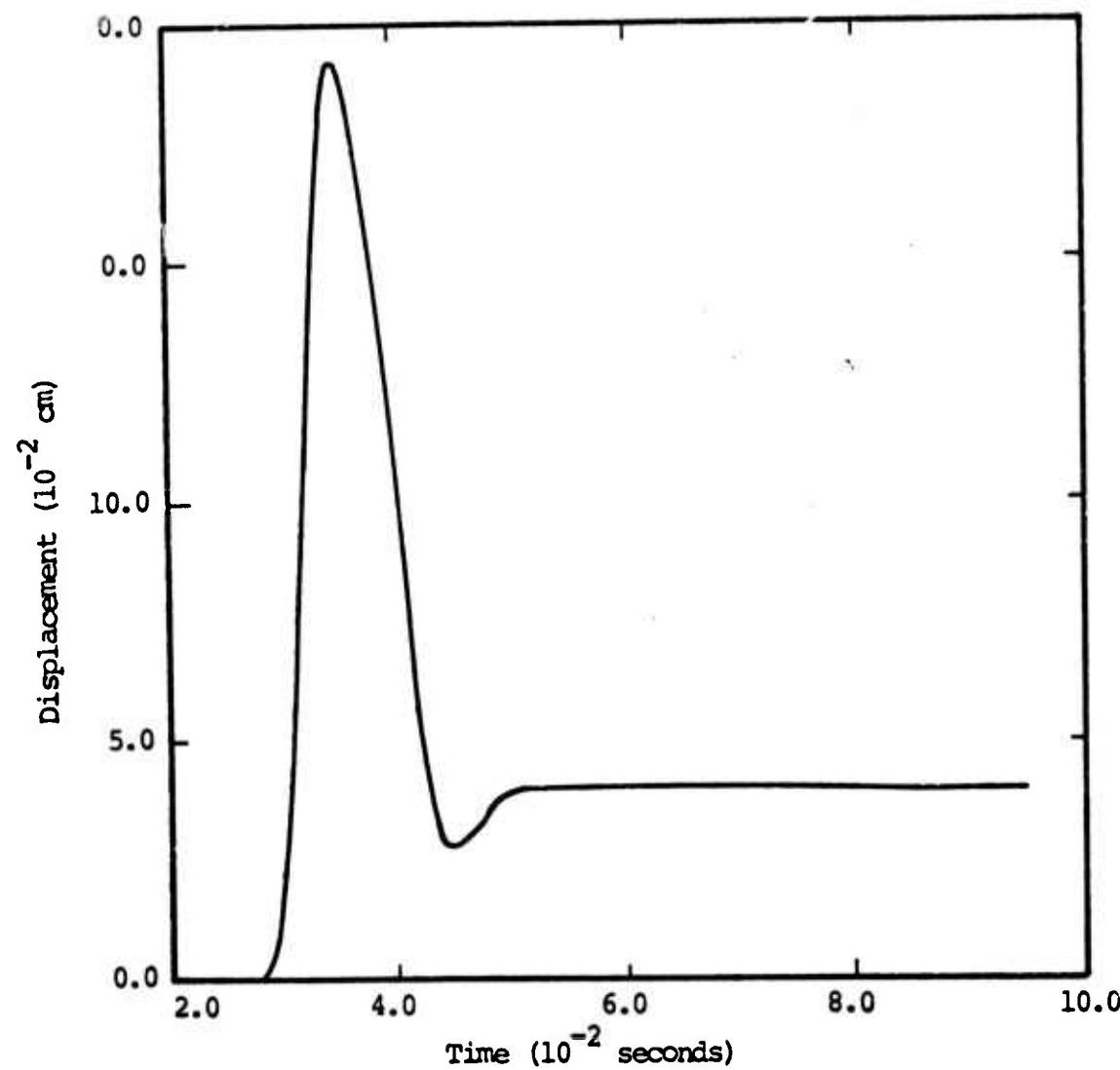


Figure 3.5. Time history of displacement monitored at a station in the elastic region, 132 meters from the explosion working point.

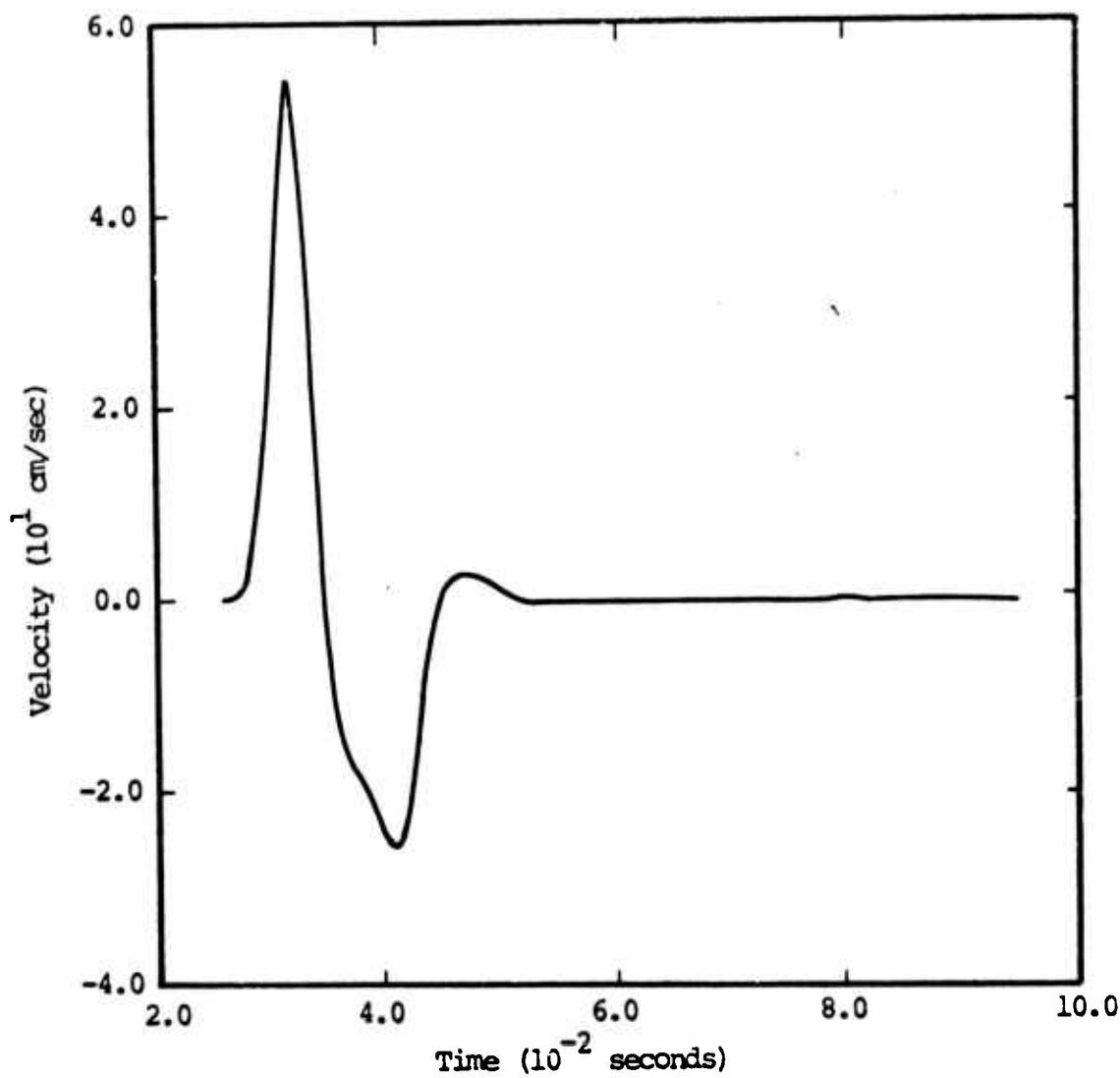


Figure 3.6. Time history of velocity monitored at same station as in Figure 3.5.

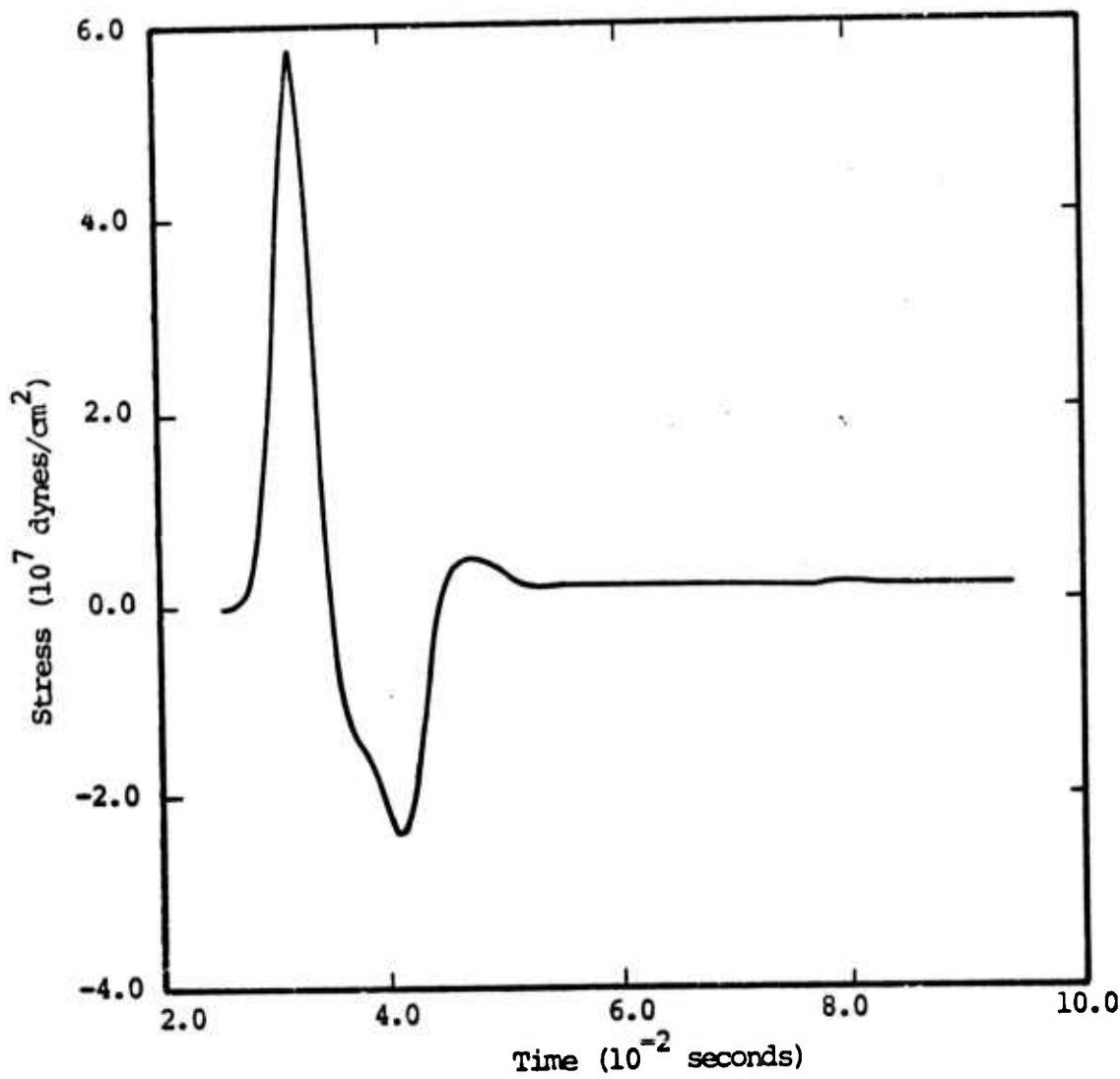


Figure 3.7. Time history of stress monitored at same station as in Figure 3.5.

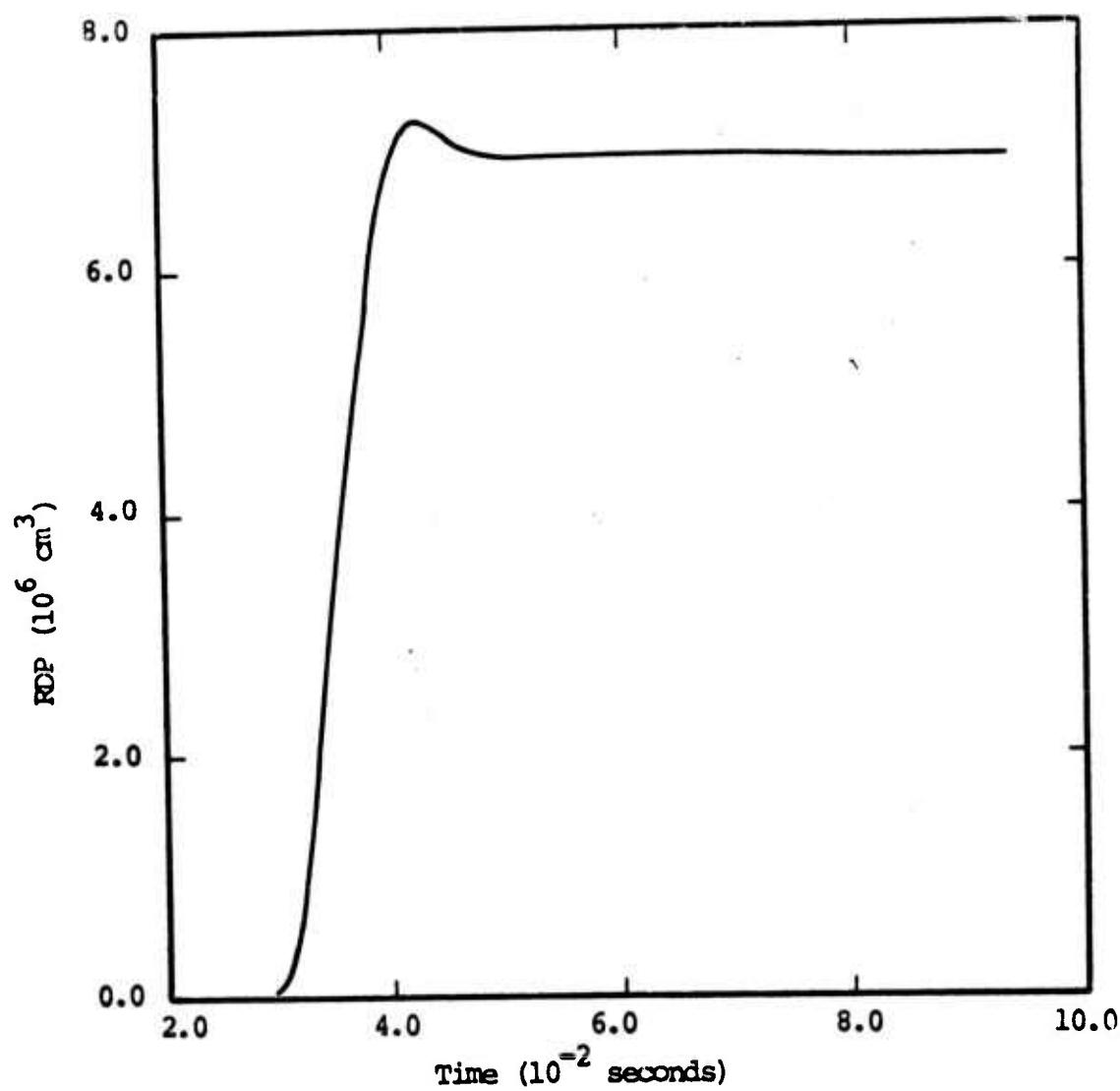


Figure 3.8. The reduced displacement potential monitored at same station as in Figure 3.5.

coupling and must be scaled to the true device yield by multiplying by the ratio of device yield to 20 tons. The cavity radius for a yield of 20 tons was computed to be 3.42 meters.

With the equivalent elastic source calculated for Mast we are now in a position to begin computation of synthetic seismograms at specified receiver locations, which were recently furnished by the Project Officer.

3.4 CODE DEVELOPMENT

A new calculational tool has been developed to facilitate those areas of the parameter study which involve phenomena not amenable to a spherically symmetric description. The inclusion of free surface generated interference effects and water table effects both require a two-dimensional description at late times. A LINK subroutine has been developed which permits the early time part of a given calculation to be performed with SKIPPER, a spherically symmetric stress wave code. The SKIPPER variables are written on tape at a time before the spherical shock reaches a free surface or submerged layer. Then, the LINK subroutine reads the tape and transforms the variables to a two-dimensional cylindrically symmetric mesh in the CRAM code. The remainder of the calculation is performed with CRAM.

A new crack model was developed and checked out in the SKIPPER code. The new model includes a variable yield surface above which all tensions are forbidden by allowing cracks to open in the appropriate direction.

Finally, considerable improvement was made to our capability for generating synthetic seismograms. Most important, the more accurate generalized ray theory approach to computing the amplitudes of seismic waves traveling through the earth's upper mantle is being tested and integrated into our library of computer codes.

IV. CONCLUSIONS

Considerable progress was made during the first three months of this project on several of the tasks specified in the work statement for this contract.

A one-dimensional parameter study which identifies the dependence of teleseismic magnitude on near source material properties was carried out. The major results of the material parameter sensitivity study may be summarized as follows:

1. Increasing the air-filled porosity greatly reduces seismic coupling.
2. If any parameter describing the yield surface is varied such that the material strength is reduced, seismic coupling may be substantially enhanced.
3. Seismic coupling is relatively insensitive to water content; a slight decoupling is observed with increasing water content.
4. Increasing the overburden pressure substantially reduces seismic coupling.

The near field coupling and the equivalent elastic source were computed for the recent underground explosion, Mast, at Pahute Mesa. The next step is to generate synthetic seismograms for this event at recently specified receiver locations. The enhanced computational capabilities for treating realistic earth structures will be exercised in this experiment.

V. REFERENCES

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